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Properties of Planetary Fluids at High Pressures and Temperatures.

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Observational data obtained by the Voyager space probes to the giant planets Jupiter, Saturn, Uranus, and Neptune have provided valuable information, which is used to refine our picture of the nature of the interiors of these planets. Major results from the Voyager missions include observations of substantial magnetic fields and improved models of internal density distributions. Our goal is to obtain equation-of-state (EOS) and electrical conductivity data for planetary gases (H_2 and He) and the "ices" (H_2O, CH_4, and NH_3, and their mixtures), which are considered to be the major constituents of the giant planets. These data are needed to test theoretical databases used to construct models of the chemical composition of planetary interiors, models which are consistent with observables such as mass, diameter, gravitational moments, rotation rate and magnetic field. The 100 GPa (1 Mbar) pressures and several 1000 K temperatures in the giant planets can be achieved in the laboratory by the shock compression of liquid specimens.

Jupiter and Saturn are thought to be composed primarily of hydrogen and helium.[1] Figure 1 shows their calculated planetary isentropes.[2] Figure 1 also illustrates the relevance of laboratory shock-compression experiments to the giant planets. The single-shock compression curve or Hugoniot of liquid hydrogen intersects the planetary isentropes near 20 GPa and 3000 to 4000 K. Even higher pressures and densities in the laboratory are achieved by reflecting a first shock in liquid hydrogen off a metal anvil, thereby causing a second shock wave. The second-shock states, or the double-shock Hugoniot in Fig. 1, achieve states close to the planetary isentropes at still higher pressures and temperatures.

Uranus and Neptune are thought to consist of an outer layer primarily of hydrogen and helium and an inner layer rich in the planetary "ices." Density distributions have been calculated for Uranus[1,3,4] from the gravitational movements derived from the observed precessions of its elliptical rings, and from its mass, radius, and rotational rate. Some models show a dense "rocky" core, although the sensitivity of the external gravitational field is weak to the relatively small mass at such great depth. The H_2-rich envelope is at radii greater than about 0.75 R_U, where R_U is the outer radius of Uranus. The region at radii less than about 0.75 R_U is the ice-rich region. The magnetic fields of these planets are produced by dynamos generated by the convection of high-temperature conducting fluids in the outer ~30% of the planetary radii.[5] Pressures extend up toward the 100 GPa range and several 1000 K in these regions.

We measured previously single- and double-shock EOS data for "synthetic Uranus," an H-rich liquid with an H:O composition ratio of 3.5:1 and abundance ratios close to cosmological for O:C(7:4) and O:N(7:1).[6] It is a solution of water, ammonia, and isopropanol (C_3H_8O) with mole fractions of 0.71, 0.14, and 0.15, respectively. Our four double-shock points are in the range 98 - 220 GPa. The maximum density achieved is 3 g/cm^3, which probes a depth of about 0.5 R_U. The region for radii >0.5 R_U is the region probed most sensitively by gravitational moments. Our double-shock EOS points are in good agreement with the planetary isentrope.[1] This agreement suggests that the outer core of Uranus might be composed primarily of the ices. However, chemical compositions cannot be derived uniquely from laboratory data alone. In the last year we performed a double-shock temperature measurement of synthetic Uranus of 4000 K at about 100 GPa. This measurement is important because theoretical temperatures of "ice" are relatively uncertain.

We recently measured four electrical conductivity data points of shocked liquid hydrogen. These data are important for understanding the magnetic fields of all the giant planets. In particular, a scaling relationship for the conductivty is needed at relevant densities and temperatures for dynamo or kinematic calculations of planetary magnetic fields. These data also provide a measure of the narrowing of the electronic bandgap of molecular H_2 with density as it approaches metallization, a subject of fundamental scientific interest. Our experiments are in the ranges 10-20 GPa, 3000-5000 K, and volumes near 8 cm^3/mol. Although our conductivity experiments are not yet complete, preliminary analysis indicates that the electrical conductivity σ scales as

$$\sigma = \sigma_0 \exp(-E_g/kT), \qquad (1)$$

where E_g is the bandgap and T is shock temperature. We used calculated values of shock temperatures.[7] Our preliminary bandgap is in agreement with recent theoretical predictions[8,9] at the molar volume of our experiments. The gap we observe is substantially higher than previous theoretical predictions.[10] The pre-exponential factor σ_0 is also substantially larger than predicted.[5]

Our measurement of the bandgap of hydrogen is the first direct one at high pressures, to our knowledge. This measurement is made possible by shock heating, which thermally activates electronic charge carriers and induces electrical conductivity. Because of the large bandgap compared to thermal energy, negligible internal energy is absorbed in electronic excitation and the equation of state of molecular hydrogen is unaffected by electronic excitation at the conditions of the experiments.

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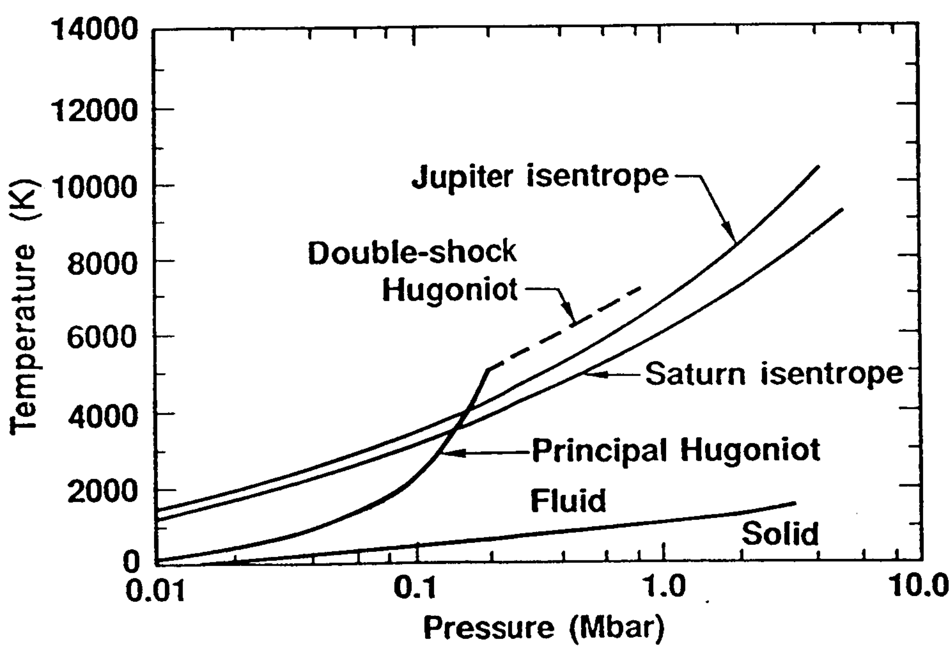

Figure 1. Isentropes of Jupiter and Saturn compared with the Hugoniot and double-shock Hugoniot of H_2, plotted as temperature versus pressure (after Ref. 2; 1Mbar=100 GPa) .